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THE RELIABILITY OF DEEP-SEA REVERSING THERMOMETERS

by

H. F. P. Herdman
and
L. H. Pemberton

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THE RELIABILITY OF DEEP-SEA REVERSING THERMOMETERS

By H. F. P. Herdman
(National Institute of Oceanography)
and L. H. Pemberton
(National Physical Laboratory)

(Figs. 1–7)

INTRODUCTION

With the advance of our knowledge of oceanography little remains to be written about the construction and methods of using deep-sea reversing thermometers; they have, in fact, become standard equipment and, in general, the performance of any individual thermometer over a period of years appears to be taken very much for granted. This uncritical attitude is no doubt associated with the more universal use of this instrument. Until fairly recent times the use of deep-sea reversing thermometers was confined largely to the few major oceanic expeditions where, on the return of the ship, the bulk of the equipment was generally sold, or stored away in some unlikely place, and forgotten. Even when sold the only information usually available to the new owners was the original certificate of calibration. Periodic checks on the zero point of all the 'Meteor' deep-sea thermometers were, however, made by Böhnecke and Wüst (Wüst, 1932) during the Expedition of 1925–7, and a critical survey of the accuracy of the reversing thermometers used in the 'Carnegie' in 1928–9 was published fifteen years later (Sverdrup, Fleming, Soule and Ennis, 1944). Wüst's check was made to determine any change in zero point during the period of the Expedition whereas the examination of the 'Carnegie' temperature readings was made to assess the reliability of the deep-sea thermometers, especially with regard to minor differences in the temperatures recorded by each pair of thermometers.* So far as we have been able to find out, no other published data exist—except for a very brief reference in the 'Carnegie' report—concerning any possible change in the characteristics, or in the behaviour generally, after their use, or storage, over a number of years. Nor has there been any comparison between thermometers by different makers. Although not specifically referring to the behaviour of deep-sea thermometers with regard to their continued use, a recent note by Whitney (1955) should perhaps be mentioned. Doubts have been expressed at the Woods Hole Oceanographic Institution about certain aspects of the behaviour of unprotected reversing thermometers, mainly in respect of the determination of the mean pressure coefficient (m.p.c. or 'Q'), and in his paper Whitney describes the re-examination, after a period of three years, of a group of such thermometers. Results of the tests were largely negative but, nevertheless, are extremely valuable in that they emphasize the individuality of these instruments and so the difficulty of attempting to codify their characteristics.

At the last check (1953–4) by the National Physical Laboratory (N.P.L.) of nearly all the deep-sea thermometers now held by the National Institute of Oceanography (N.I.O.), some eighty of these instruments were examined. Of these, thirty-six protected and two unprotected deep-sea reversing thermometers had been the property of the Discovery Committee, and had been in use or, when not

* Mostly two protected thermometers were used by the 'Carnegie' at each depth—a practice adopted for all depths by the Discovery Committee and, in turn, by the National Institute of Oceanography.

in use, had always been kept in an upright position, over periods varying between fifteen and twenty-nine years. The records of these thermometers over such exceptionally long periods are probably unique. In this paper, therefore, after a review of the errors and eccentricities to which deep-sea thermometers are liable, we can examine the general question whether or not they change or deteriorate with age. We hope to show that most thermometers, at least of certain British and German makes, can continue to give good service for very long periods, provided they are properly cared for; and that there is little change with age apart from a tendency for the zero point to rise.

All the thirty-eight thermometers had previously been re-certified at least once, after the issue of the original certificate of test. Sixteen of the thirty-six protected thermometers were made in Germany prior to 1926 (by Richter and Weise, of Berlin); the remainder were made at various times between 1934 and 1938 by Negretti and Zambra, of London. The scale range varies considerably, but all are divided to 1/10° C. In 1953–4 certificates were issued in respect of thirty-three protected thermometers only, as the mercury column of each of the remaining three (of German origin) consistently refused to break at the constriction or appendix when the thermometer was reversed unless the thermometer was tapped. The action of these thermometers had, however, been satisfactory when they were previously examined by the N.P.L. in 1949. It is unfortunate that only two unprotected thermometers of any considerable age have survived for comparison but, in view of their extreme vulnerability, this is not, perhaps, surprising.

Errors and Eccentricities

Although the zero point of a reversing thermometer* is dependent on the 'break-off' action of the mercury column at the constriction or appendix peculiar to this type of thermometer, there is a characteristic rise (of the order of a few hundredths of a degree) of zero with age very similar to that which commonly takes place in ordinary mercury-in-glass thermometers; except for this rise of zero the majority of deep-sea thermometers appear to maintain their accuracy remarkably well for many years—whether in store or frequent use—provided that they are properly cared for. That a few become erratic in their habits after repeated use, is not surprising; for instance, those used for observations at the greater depths may, if used in tropical waters, be cooled rapidly from 28° to 1° C. between the surface and a depth of 5000 m., and as quickly heated again when returning to the surface.

Erratic readings from deep-sea thermometers usually result from only a few basic causes, the commonest of which is the presence of a minute bubble of gas in the column of mercury, somewhere in the capillary of the thermometer. On reversal the mercury column breaks at the point where the bubble is then situated. Rough handling of a thermometer is usually the reason for the occurrence of this condition which, nevertheless can occur in normal use even when the greatest care is taken to protect the instrument from shock.

One eccentricity, however, for which it is difficult to find a satisfactory explanation is the failure of the column of mercury to break at all, unless the thermometer is tapped. With very low temperatures this is perhaps understandable, since the amount of mercury concerned is small and, if reversal is unusually slow, the weight of mercury involved might not be sufficient to overcome the surface tension and bring the constriction into action. (We revert to this point below, p. 238, when considering the histories of the various thermometers.) There is no evidence, however, that the amount of mercury reversed determines whether the thread breaks or not. This eccentricity can occur at all

* Deep-sea reversing thermometers comprise two thermometers—main and auxiliary. Since the latter is a conventional, or standard type of thermometer it has not been considered in this paper, and any reference to a reversing thermometer should be taken as referring to the main thermometer only.

depths, and over the whole range of ocean temperatures, and it may be that with repeated use some physical change of a purely temporary nature takes place in the structure of the glass; such a change may affect a particular constriction or appendix (in themselves a tribute to the glassblower's skill) sufficiently to upset the normal action of the thermometer. If, however, a thermometer which behaves erratically in this manner is 'rested' for some months—in an upright position—it will usually behave normally when returned to service. This recovery of normal accuracy after 'resting', and without 'manipulation' of the thermometer,* seems to be strong evidence for a temporary change in the structure of the glass.

Calibration and Certification of Deep-sea Reversing Thermometers

The original certificates of scale correction for the thirteen German thermometers under review were issued in 1924 and 1925 by the Physikalisch-Technische Reichsanstalt (P.T.R.) of Berlin, who also re-examined some of them in 1933 and 1935. Unfortunately, the N.I.O. does not now possess the original (1924–5) certificates for the three thermometers (nos. 1008, 1011 and 1257) re-examined by the P.T.R. in 1933, nor for those re-examined in 1935 (nos. 863, 883 and 1019). An attempt was made to obtain copies of these German certificates, but this was not possible since all pre-war thermometric records of the P.T.R. were lost during the bombing of Berlin.† All checks on the German thermometers, subsequent to 1935, have been made at the N.P.L. The original calibration of the British thermometers now under review, and all subsequent checks, were also made at the N.P.L.

The limits of accuracy of the P.T.R. calibrations of the main thermometer, as given on their certificates, were $\pm 0{\cdot}01^\circ$ C.; the limits quoted by the N.P.L. were, up to and including the year 1938, also $\pm 0{\cdot}01^\circ$ C.; in 1949 and 1953 they were $\pm 0{\cdot}02^\circ$ C. This change was actually made in 1939 but it is of interest to note that in 1929, in connection with tests on a protected deep-sea thermometer (of the range -2° to $+16^\circ$ C.) made by Richter and Weise, the N.P.L. would only give a certificate of corrections to $\pm 0{\cdot}02^\circ$ C. Messrs Negretti and Zambra, in commenting on this,‡ wrote as follows: '. . . they (the N.P.L.) report to us that, a number of tests having been carried out, the reproductivity of the readings does not admit giving the corrections closer than $\cdot 02^\circ$ C., and we must say that we rather agree with them when $1^\circ = 8$ mms. . . .' Of the thermometers now under review those of German make, with one exception, differ only slightly in range and, apart from this exception, the length of 1° on the scale of the main thermometers of the remainder varies between 8·1 and 9·1 mm. The thickness of the graduation line is approximately 0·05 mm. The range of the British thermometers is the same throughout (-2° to 12° C.), with the length of one scale degree varying between 9·6 and 11·3 mm. The average is 10·5 mm. The thickness of the graduation line is, approximately, 0·1 mm. This slightly more open scale is, no doubt, a help towards more accurate readings but still does not warrant corrections being determined to a greater degree of accuracy than $\pm 0{\cdot}02^\circ$. That it is possible in field-work to read these thermometers to a greater degree of accuracy cannot be gainsaid. Any experienced observer expects to obtain readings accurate to $\pm 0{\cdot}01^\circ$ C.

* 'Manipulation' is the comprehensive term used to describe all aspects of the corrective treatment used when trying to restore a temporarily erratic thermometer to its normal action (Whitney, 1952).

† Personal communication to one of the authors (H.F.P.H.).

‡ Letter from Messrs Negretti and Zambra, dated 29 October 1929, to the Director of Research, Discovery Committee. This extract is published by permission of Messrs Negretti and Zambra.

Table 1. *Protected deep-sea thermometers*

(1) Ships and commissions: D.—R.R.S. 'Discovery', 1925–7; D. II—R.R.S. Discovery II', 1929–31, 1931–3, 1933–5, 1935–7, 1937–9 and 1950–1; WS.—R.R.S. 'William Scoresby', 1928–9, 1929–31, 1931 and 1950.

(2) The figures in parentheses after the commissions of the various ships are the number of times the thermometer concerned was used on that commission.

(3) An assessment of the reliability is available only for the following commissions: R.R.S. 'Discovery', 1925–7; R.R.S. 'Discovery II', 1929–31, 1933–5, 1937–9 and 1950–1; R.R.S. 'William Scoresby', 1950.

(4) When the expression 'no comments' is used in connection with thermometers whose reliability has been assessed, it may be assumed that the action was entirely satisfactory.

Thermometer no.	*Range* (° C.)	*Vol.* (°)	*Zero error* (° C.) 1924†	1925†	1933†	1934	1935†	1937	1938	1949	1953	*No. of times used*	*Ships and commissions on which used*	*Reliability*
854	−2/19·3	152	−0·01	—	—	—	—	—	—	0·02	0·02	—		Apparently not used
863	−2/19	154	*	—	—	—	−0·04	—	—	−0·01	−0·02	112	D. II 35/37 (66), 37/39 (44) and 50/51 (2)	Mercury stuck in expansion chamber once (37/39)
869	−2/17·9	166	−0·06 [−0·66]	—	—	—	—	—	—	Nil	0·01	12	D. 25/27 (10); D. II 50/51 (2†)	Two completely erroneous readings (50/51)†
871	−2/18·8	265	Nil	—	—	—	—	—	—	0·01	0·02‡	5	D. 25/27	No comments
876	−2/18·2	209	−0·01	—	—	—	—	—	—	0·01	0·01	11	D. 25/27	No comments
883	−2/17·3	238	*	—	—	—	0·02	—	—	Nil	0·01	1	D. II 37/39	Completely erroneous reading (37/39)
971	−2/25	97		0·05	—	—	—	—	—	0·01	0·01	3	D. II 50/51	No comments
1008	−2/18·5	127	*		0·02	—	—	—	—	0·02	0·05	27	D. 25/27 (5); D. II 31/33 (6), 35/37 (4) and 37/39 (12)	Twice failed to 'break' (37/39)
1011	−2/18·1	93	*		0·01	—	—	—	—	0·03	0·03	116	D. II 35/37 (63), 37/39 (37) and 50/51 (16)	In collision (37/39). Twice failed to 'break' (50/51)
1019	−2/19·5	150	*				Nil	—	—	0·02	0·01	51	D. 25/27 (9); D. II 37/39 (42); WS. 50 (1†)	Mercury stuck in expansion chamber once (50)†
1023	−2/18·5	155		Nil	—	—	—	—	—	0·03	0·04	38	D. 25/27 (13); WS. 50 (25)	Two completely erroneous readings (25/27) and (50)
1025	−2/18·7	156		Nil	—	—	—	—	—	0·02	0·03	68	D. II 29/31 (29), 31/33 (2), 37/39 (24) and 50/51 (13)	No comments
1257	−1·3/17·3	114			−0·03	—	—	—	—	−0·01	Nil	459	WS. 28/29 (101), 29/31 (38) and 31 (46); D. II 35/37 (193) and 37/39 (81)	No comments
CD 5556	−2/12	55				−0·01	—	—	—	Nil	0·01	49	D. II 33/35 (29), 35/37 (4), 37/39 (15) and 50/51 (1)	Erratic at times (33/35, 37/39 and 50/51)

Table 1 (*cont.*)

Thermometer no.	*Range* (° C.)	*Vol.* (o°)	*Zero error* (° C.) 1924†	1925†	1933†	1934	1935†	1937	1938	1949	1953	*No. of times used*	*Ships and commissions on which used*	*Reliability*
CD 5559	−2/12	61				Nil	—	—	—	0·05	0·02	297	D. II 37/39 (240) and 50/51 (57)	Two impossible readings and once stuck (37/39). No comments (50/51)
CD 5563	−2/12	55				−0·03	—	—	—	0·01	Nil	271	D. II 33/35 (172), 35/37 (2), 37/39 (66) and 50/51 (31)	Erratic (33/35). Two impossible readings, and once stuck (37/39). No comments (50/51)
CG 11309	−2·5/12	70						Nil	—	0·02	0·04	216	D. II 37/39 (209) and 50/51 (7)	Four erroneous readings and once stuck (37/39). Erratic over a period (50/51)
CG 15243	−2·5/12	104						−0·01	—	−0·03	−0·01	259	D. II 37/39 (252), WS. 50 (7)	Stuck once (50)
CH 17798	−2·5/12	49							0·01	0·04	0·05	169	D. II 37/39 (168), WS. 50 (1)	Irregular action (50)
CH 17799	−2·5/12	55							0·01	0·01	0·04	2	WS. 50	Stuck once (50)
CH 17800	−2·5/12	49							0·01	0·02	0·04	179	D. II 37/39 (155), WS. 50 (24)	One impossible reading (37/39)
CH 17801	−2·5/12	64							Nil	0·01	0·03	72	D. II 37/39 (48), WS. 50 (24)	One impossible reading (37/39). Twice failed to break (50)
CH 17803	−2·5/12	61							Nil	0·02	0·04	191	D. II 37/39 (168), WS. 50 (23)	One impossible reading (37/39)
CH 17804	−2·8/12	70							Nil	0·02	0·05	90	D. II 37/39 (68), WS. 50 (22)	No comments
CH 17805	−2·5/12	58							0·01	0·03	0·06	8	WS. 50	Stuck once (50)
CH 17808	−2·5/12	58							Nil	0·01	0·03	176	D. II 37/39	No comments
CH 22676	−2·5/12	61							Nil	0·07	0·08	104	D. II 50/51	One erroneous reading (50/51)
CH 22677	−2·5/12	67							Nil	Nil	0·03	55	D. II 50/51	No comments
CH 22678	−2·5/12	61							Nil	0·03	0·04	108	D. II 50/51	One erroneous reading (50/51)
CH 22679	−2·5/12	70							Nil	0·04	0·07	111	D. II 50/51	No comments
CH 22680	−2·5/12	58							Nil	0·01	0·03	77	D. II 50/51	No comments
CH 22681	−2·5/12	61							Nil	0·04	0·04	—	—	Not used
CH 22683	−2·5/12	73							Nil	0·05	0·07	102	D. II 50/51	No comments

* The original certificates for these thermometers cannot now be found. It is, however, virtually certain that the original certificates were issued in 1924 or 1925.

† Thermometers in these years checked by Physikalisch-Technische Reichsanstalt. Remainder of certificates by National Physical Laboratory.

‡ In 1953 a statement of examination only was issued by the N.P.L. in respect of this thermomenter. Since the refusal of a certificate was solely on account of the large corrections required to the *auxiliary* thermometer the particulars relating to the main thermometer have been included in this table.

PROTECTED THERMOMETERS

Change with Age in the Zero Point and Scale Corrections

Most of the information concerning the thermometers under review is best given in tabular form. In Table 1 we have, therefore, listed the physical particulars for the protected deep-sea thermometers, i.e. range, volume of mercury reversed at 0° (usually referred to as V_0) and the periodic zero error, together with data regarding the thermometers when actually in use. Unfortunately these data are not as complete as we would wish; for certain thermometers they are, however, considered sufficient to give a reasonable indication of the reliability to be expected from that instrument.

The table shows that the zero point generally rises with increasing age. This is a normal characteristic of all conventional, or standard type thermometers and, as already mentioned, reversing thermometers do not seem to provide any exception to this rule. Generally any major shift of zero occurs in the early years of the life of a thermometer, a fact seemingly borne out by the figures available for our protected deep-sea instruments. If we consider the various age groups in order, the following facts concerning the zero point appear.

29-*group* (1924–53). Four thermometers—nos. 854, 869, 871 and 876. Only one thermometer (869) shows a zero drift of more than 0·03° and, for all thermometers, the greater part of the drift took place between the years 1924 and 1949. Between checks in 1949 and 1953 two thermometers registered nil drift and the other two only 0·01°. All of Richter and Wiese's make. First check at P.T.R., remainder by N.P.L.

28-*group* (1925–53). Three thermometers—nos. 971, 1023 and 1025. Drift of zero point for all three thermometers very similar. Maximum drift 0·04°, minimum 0·03°, with the major change again occurring before 1949. Between 1949 and 1953 no change for one thermometer, 0·01° for the others. First check at P.T.R., remainder by N.P.L. All of Richter and Wiese's make.

20-*group* (1933–53). Three thermometers—nos. 1008, 1011 and 1257. Little change in period under review. Maximum shift of zero was 0·03°, minimum 0·02°. Two thermometers showed major drift between 1933 and 1949; the zero of the remaining one was constant between these dates but shifted 0·03° between 1949 and 1953. Of Richter and Wiese's make and it is virtually certain that they were made, and originally calibrated by the P.T.R., before 1925. This information cannot now be checked (see p. 233). One known check by P.T.R., two by N.P.L.; thermometers nos. 1011 and 1257 extensively used, especially the latter.

19-*group* (1934–53). Three thermometers—nos. CD 5556, 5559 and 5563. All from one batch of twelve made by Negretti and Zambra. Maximum drift of zero, 0·05°, minimum 0·02°. One thermometer normal, with rise of zero point over whole period; the remaining two, after a rise between 1934 and 1949, showed a fall of zero between 1949 and 1953. All checks by N.P.L. Although extensively used, the behaviour of the whole batch was generally erratic. It is only fair to say, however, that after a lapse of many years Negretti and Zambra had not long begun again to make reversing thermometers.

18-*group* (1935–53). Three thermometers—nos. 863, 883 and 1019. Zero points remarkably constant over period but, as in the 20-year group, it is virtually certain that the calibration by the P.T.R. in 1935 was a re-calibration, and that the thermometers were originally calibrated there in 1924 or 1925. All made by Richter and Wiese. One check by P.T.R., two by N.P.L.

16-*group* (1937–53). Two thermometers—nos. CG 11309 and CG 15243. Sole survivors of two separate batches of six instruments each. Zero of no. 11309 shows a steady rise over the whole period; that of no. 15243 fluctuates. Of Negretti and Zambra's manufacture. All calibrations by N.P.L. Both thermometers used extensively but CG 11309 was, at times, rather erratic.

15-*group* (1938–53). Fifteen thermometers—nos. CH 17798 etc., and CH 22676 etc. comprising eight and seven thermometers respectively from two batches of twelve made in 1938 by Negretti and Zambra. First batch shows in general a much more regular drift of zero than the second batch, of which all now under review had a nil correction to zero at first calibration. No obvious reason for this difference is apparent; both batches were made by the same, and at that time the senior, operative on this work. All checks by N.P.L. Extensive use generally, with only a few minor and unimportant failures.

Normally, a shift of zero point should be reflected equally in the scale corrections throughout the whole range of a conventional thermometer, and this holds good also for protected reversing thermometers. Correction graphs for each calibration of all the thermometers listed in Table 1 have been drawn and, with only a few exceptions, there is a considerable similarity in the general trend of the correction curve at each calibration of individual thermometers. Those made by Richter and Wiese show, in general, less variation in the scale corrections required over the whole range, and over the years but, despite the larger and sometimes more irregular scale corrections required to a number of the thermometers made by Negretti and Zambra (possibly because of a slightly more irregular bore in the glass tubing), there is a more marked similarity in the trend of the various calibration curves for each instrument. Since it is easier to demonstrate the change of zero and scale corrections graphically,

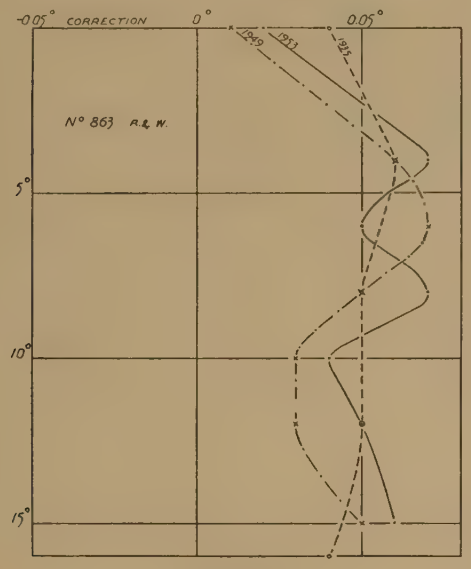

Fig. 1

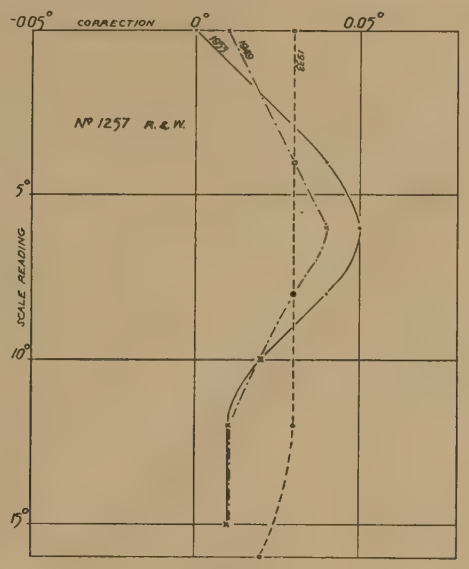

Fig. 2

typical correction graphs for two German and three British thermometers have been selected and appear as Figs. 1–5. Each comprises the correction curves for the various calibrations, with the actual scale correction plotted against the scale range.

Effect of the Volume of Mercury (V_0)*

Of the thirteen German-made thermometers listed in Table 1 three (nos. 863, 1011 and 1257) have been extensively used, especially no. 1257 with which 459 observations were made between 1928 and 1939. Four others were used to a lesser degree, whereas the remaining six appear to have had little or no use. Unfortunately the early history of these thermometers is obscure as notes on their performance were not regularly kept. We cannot say, therefore, whether they are reliable, or whether they had been used and found erratic.

On the other hand the stock of reversing thermometers carried in the ships has always been well in excess of immediate demands. Once in use a good working set of thermometers remained so until individual instruments were lost, or broken, or became erratic in their action. In these circumstances

* V_0 is the volume of mercury, in degrees, reversed at 0° C. It is determined for each thermometer by the maker. It is not, so far as we are aware, re-determined at any subsequent re-calibration.

it was quite possible for a thermometer only to have been brought into use for a few stations at the end of a commission (normally twenty months), or not to have been used at all.

Nevertheless, it is perhaps significant that the constant V_0 for three of the German thermometers least used is $>200°$ (max. 265°). This large value for V_0 inevitably entails a large and often badly shaped expansion chamber at the top of the bore, and so to a tendency for the mercury to stick in this

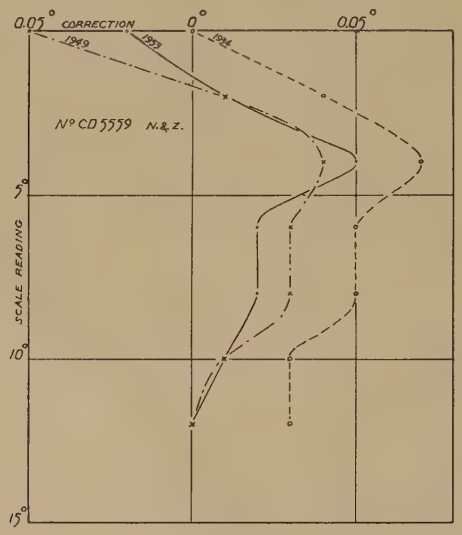

Fig. 3

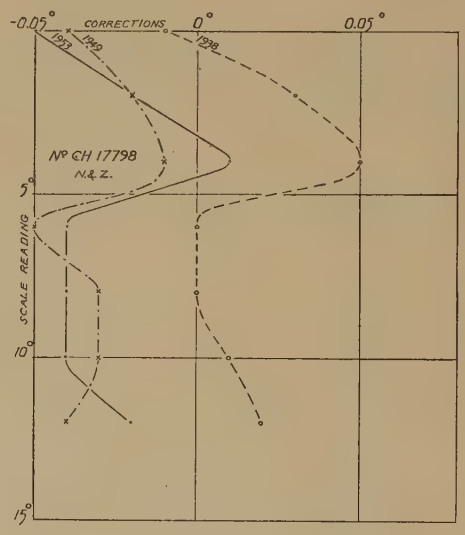

Fig. 4

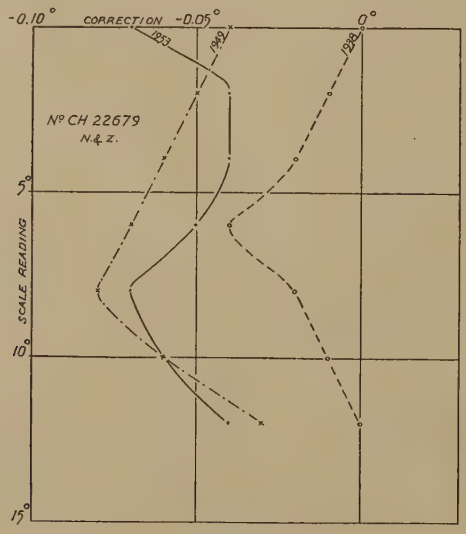

Fig. 5

chamber, instead of running back to the main bulb, when the thermometer is reset. It has already been mentioned that at the N.P.L. check in 1953–4 three other German-made thermometers of the earlier age groups (24, 22 and 20 years) failed to meet the requirements for a certificate. All were condemned for the same failure, i.e. the mercury column did not break at the constriction unless the thermometer was tapped. For these instruments the value for V_0 was less than half the figure mentioned above, but was still considerably larger than that of present day thermometers.

V_0 differs from thermometer to thermometer. Some years ago its value varied widely (reference to Table 1 shows a variation between 49° and 265°) but it has now been stabilized—at any rate in British instruments—within what appear to be reasonable limits, though the size of the expansion chamber is still determined to some extent by convenience of construction, and no two manufacturers are likely to agree on an ideal size. It is, however, generally agreed that high volumes should be avoided. It might perhaps be thought that the different weights of mercury below the constriction with different values of V_0 would be reflected in the performance of individual thermometers; this, as mentioned above, does not appear to be borne out in practice. So far as we can see there is no connection between V_0 and the performance of a thermometer, other than the tendency of those with a high V_0 for the mercury to stick in the expansion chamber.

Incidence of Failures

In Table 2 the number of successful temperature observations is related to the number of failures. It is based on (*a*) the scientific log-books kept in the ship for each voyage since 1925 which record all deep-sea temperatures taken, together with the thermometer numbers; (*b*) the temperature correction

Table 2. *Number of observations and incidence of failures in German and British thermometers*

		Make of thermometer and number of observations		*Failures*			
				German		*British*	
Ship	*Commission*	*German*	*British*	*No.*	*Age (%)*	*No.*	*Age (%)*
Discovery	1925–7	678	—	24	3·5	—	—
William Scoresby	1926–7	150	—	18*	12	—	—
William Scoresby	1928–9	926	—	26	2·8	—	—
Discovery II	1929–31	1777	137	38	2·1	4	2·9
William Scoresby	1929–31	363	—	11	3·0	—	—
William Scoresby	1931	941	—	13	1·4	—	—
Discovery II	1931–3	2275	1780	55	2·4	14	0·8
Discovery II	1933–5	2486	901	53	2·1	40†	4·4
Discovery II	1935–7	2921	129	45	1·5	10‡	7·7
Discovery II	1937–9	762	3334	25	3·3	37	1·1
William Scoresby	1950	84	111	2	2·4	6	5·4
Discovery II	1950–1	242	1861	5	2·1	21	1·1

* Mostly one erratic thermometer.
† Mainly one poor batch of thermometers.
‡ Mostly due to one erratic thermometer from 1933/5 batch.

Table 3 summarizes the figures in Table 2 for the whole period 1925–51.

Table 3. *Summary of Table 2*

		Failures	
Make of thermometer	*No. of observations*	*No.*	*Age (%)*
German (R. and W.)	13,605	315	2·31
British (N. and Z.)	8,253	132	1·60
Totals	21,858	447	2·04

books kept from 1933 onwards; and (*c*) a thermometer log kept personally by one of the writers of this paper. Separate figures are shown for British and German thermometers and failures have only been classified as such when due to one or other of the following: mercury failing to break at the constriction, mercury sticking in the expansion chamber when the thermometer is reset, and uncertain causes of anomalous temperatures. No account has been taken of the erratic behaviour of thermometers after

being in collision, or suffering shock of any other kind, nor have losses on station, or accidental breakages, been included. When a thermometer suspected of giving anomalous readings was checked several times against a reliable thermometer only one 'failure' was recorded for the whole series of comparisons.

In view of the difficulty of making reversing thermometers, and the unavoidably rough usage which they receive at times in bad weather at sea we think it is remarkable that the overall percentage of failure—just over 2%—is so low. Ignoring the continued use by the 'William Scoresby', in 1926–7, of one erratic thermometer, the percentage failure of German-made thermometers for the period 1925–51 averaged 2·25 and, in general the performance of these instruments was remarkably steady. The earliest figure of 3·5% failures, in 1925–7, was on the first occasion of their use, and before we had experience in spotting idiosyncrasies. Later, in 1931 in the 'William Scoresby', and in 1935–7 in the 'Discovery II', almost the same set of reliable German thermometers was in use throughout each period, with a consequent and marked reduction in the number of failures. For the 'William Scoresby' the percentage of failure was 1·38 for 941 observations, and for 'Discovery II' 1·54 for 2921 observations.

Except for the commissions of 1933–5 and 1935–7 of 'Discovery II', when the number of failures was increased considerably by the use of one rather erratic batch of thermometers (of which three, nos. CD 5556, 5559 and 5563 remain in use), the British-made deep-sea reversing thermometers have been equally, if not more, satisfactory. They have maintained their accuracy well and for all other commissions of 'Discovery II' they were extensively used (for 7112 temperature observations out of a total of 8142), with a percentage of failure of only 1·07. Even if the figures for the 'William Scoresby's' commission of 1950 are included, this percentage failure is increased only to 1·17.

UNPROTECTED DEEP-SEA REVERSING THERMOMETERS

Earlier in this paper it was mentioned that only two pre-war unprotected reversing thermometers had survived for comparison with each other. Actually, four such instruments remain but of these the history of two is obscure. They do not appear to have been used, nor to have been re-calibrated more than once, and their characteristics have not therefore been considered. In addition, fifteen post-war unprotected thermometers remain from a batch made in 1949; some of these were fairly extensively used in 'Discovery II' in 1950–1 and all have since been re-calibrated once. The scale limits of both pre- and post-war instruments is $-2°$ to $+60°$ C.

Zero Point

One of the pre-war thermometers (no. CC 14318) was calibrated by the N.P.L. in 1933, 1950 and 1954. A normal rise of zero point ($+0·04°$ C.) was observed over this period but there is little resemblance between the trend of the scale corrections in 1933, and those of later years, though closer agreement exists between these last determinations. The scale corrections for thermometer no. CG 15290 (determined in 1937, 1949 and 1954) show no agreement whatsoever between the various calibrations. A correction graph for each thermometer comprising the various scale corrections at each calibration has been drawn. These appear as Figs. 6 and 7. On the other hand, the scale corrections for the fifteen post-war instruments show a remarkable similarity in their trend at their re-calibration in 1954. Only in three instances has there been no shift of zero point since the original check in 1950; for the remainder there is the normal rise, which is reflected equally throughout the scale.

Mean Pressure Coefficient ('Q')

The mean pressure coefficient (m.p.c.) used in calculating the depth from the reading obtained upon reversal of an unprotected deep-sea thermometer, and referred to in the depth equation as 'Q', is defined as the increase in apparent temperature, in ° C., due to a pressure of 1 kg. per sq. cm. The determination of this coefficient is made at the N.P.L. by supporting the thermometer in a stout steel cylinder, containing a light oil. The cylinder is immersed in melting ice (0° C.), and pressure is applied and maintained constant for a suitable time to establish thermal equilibrium. The cylinder containing the thermometer is then reversed, and the thermometer is removed and immersed in ice to the reading.

Prior to 1950 the m.p.c. given on all certificates issued by the N.P.L., in respect of this type of thermometer, was determined at three points on the scale; since 1950, however, determination has been made at only two points. The average pressures applied at the original calibration and the limits of the scale reading (for existing N.I.O. thermometers) are shown in Table 4 below.

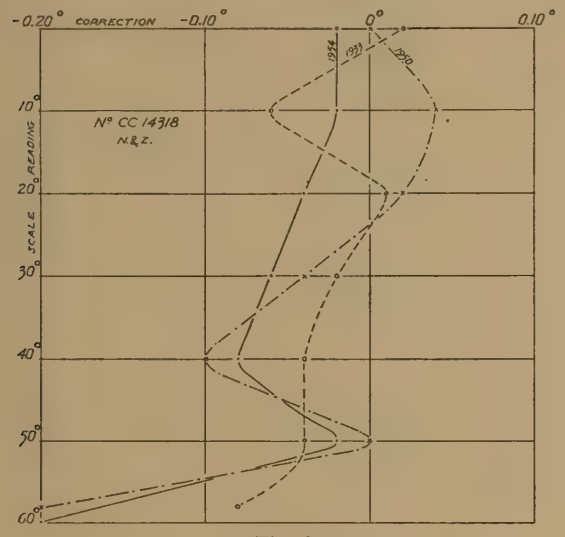

Fig. 6

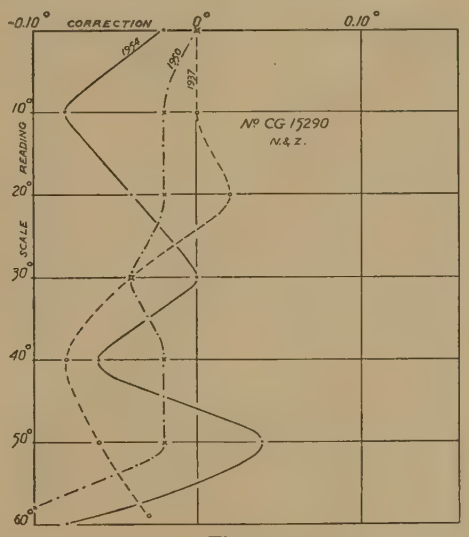

Fig. 7

Table 4. *Limits of accuracy of mean pressure coefficient*

Average test pressures in kg./cm.²		*Range of increased thermometer reading in* ° C. *(approx.)**	*Estimated accuracy of m.p.c.* (° C. *per kg./cm.²*)
3-point determination	*2-point determination*		
157·5	—	13–17	±0·0005
283·5	284·74	24–30	±0·0002
525·2	537·20	45–56	±0·0001

* Different for each thermometer, as it is dependent on the diameter of the capillary and thickness of the walls of the bulb.

In most unprotected thermometers the m.p.c. is remarkably constant over the range of pressure covered by the calibration and is about 0·1° C. per kg./cm.². Reference to Wüst (1932) shows that out of forty-seven thermometers of this type carried by the 'Meteor' only in one instance was there any difference greater than 0·0010° C. kg./cm.² in the m.p.c. at the original calibration, over the whole test range. On the return of the 'Meteor' the surviving thermometers were re-calibrated and the change in the average m.p.c. noted. Differences varied between nil and 0·0013, with an average for

eighteen thermometers of 0·0004. After the sixth commission of the 'Discovery II' (1950–1) nineteen unprotected thermometers—all of British make—remained available for use. Four of these were of pre-war origin; the remainder were made in 1949. Seventeen were re-calibrated in 1954 and, for reasons which will be explained later, a more detailed check of the m.p.c. has been made in respect of four of these. So that comparison can easily be made with the 'Meteor' thermometers, the particulars relating to the 'Discovery II's' thermometers have been similarly arranged in Table 5, but without the full particulars of the detailed check.

With one exception the figures in Table 5 show a marked stability in the m.p.c. Not only is there close agreement between the values at different points on the range of individual thermometers but, as in the German-made thermometers of the 'Meteor' Expedition, little change has occurred over periods varying between four and seventeen years. These figures, in fact, indicate that determination of the m.p.c. from observations at atmospheric pressure and at two elevated pressures is probably sufficient, and that an average of the values thus obtained is sufficiently accurate for all depth calculations in dynamical oceanography. It is interesting to note that certificates issued by the P.T.R., between 1925 and 1931, in respect of unprotected thermometers made by Richter and Wiese, and held by the Discovery Committee, gave only one value for the m.p.c. to cover the whole scale range. In view of the information available from Wüst's critical examination (1932) it is virtually certain that this value for the m.p.c. was an average of two or more determinations at different points on the scale.

As we have already shown (Table 4) the lowest range on the scale over which the m.p.c. for the N.I.O. thermometers was determined was 0° to about 13° C., for determinations at three elevated pressures. For 2-point determination the lowest range was 0° to about 24°. Recently, one fishery research laboratory has found it necessary to use unprotected thermometers at much shallower depths than hitherto considered necessary. All thermometers of this type then held by them had been certified by the N.P.L. for m.p.c. at the usual three points, and they inquired whether it would be correct to assume that, if these values were plotted, a value for the m.p.c. at a lower point on the scale could be obtained by extrapolation. At the time of this query all the unprotected thermometers listed in Table 5 were with the N.P.L. for re-certification. It was arranged that some of them, instead of being checked only at the now-customary two points, should be checked over the whole range. Four thermometers, nos. CC 14318, DI 18225–6 and DI 18232 were chosen and observations made at seven elevated pressures. The estimated accuracy of the measurement of increase of thermometer reading after the application of pressure was $\pm 0{\cdot}05°$ C. This uncertainty affects the computed value of the m.p.c. by an amount which varies with the pressure range used. For example, at a pressure of 34·80 kg./cm.^{2}, the estimated accuracy of the m.p.c. was $\pm 0{\cdot}0015$ while at 536·41 kg./cm.^{2} the value was $\pm 0{\cdot}0001$. From the figures obtained it seemed at first sight that extrapolation of the m.p.c. for scale points below the normal test points would be difficult but, when the increase of the thermometer reading was examined arithmetically, and graphically, it was found that this increase was linear within the limits imposed by the uncertainty of the actual measurements. Taking into consideration the other errors which may occur in field-work, it is unlikely therefore that any additional small error due to taking a mean m.p.c. over the whole pressure range will have a significant effect on the computation of depth, the limit of accuracy of which is approximately ± 1 m. for each 1000 m. of depth.

Table 5. *Calibration of unprotected thermometers for mean pressure coefficient*

Thermometer no.	Original calibration: Date	Original calibration: Test pressure (kg./cm.²)	Original calibration: m.p.c.	Original calibration: Average	Re-calibration 1949–50 (average m.p.c.)	Re-calibration 1954 (average m.p.c.)	m.p.c. Difference between first and last check	Number of times used (total for all commissions)
CC 14316	1933	157·5 283·5 551·2	0·0990 0·0988 0·0987	0·0988	0·0990	—	0·0002	161
CC 14318	1933	157·5 283·5 551·2	0·1004 0·1005 0·1006	0·1005	0·1005	*0·1012 (0·1007)	*0·0007 (0·0002)	243
CG 15290	1937	157·5 283·5 519·5	0·1066 0·1071 0·1079	0·1072	0·1078	0·1078	0·0006	67
CG 15291	1937	157·5 283·5 519·5	0·1086 0·1098 0·1107	0·1097	Not tested	0·1106	0·0009	—
DI 18225	1950	284·74 537·20	0·0955 0·0953	0·0954	—	*0·0955 (0·0954)	0·0001	104
DI 18226	1950	284·74 537·20	0·0946 0·0948	0·0947	—	*0·0945 (0·0946)	*0·0002 (0·0001)	108
DI 18227	1950	284·74 537·20	0·0956 0·0957	0·0956	—	0·0956	Nil	79
DI 18228	1950	284·74 537·20	0·1043 0·1045	0·1044	—	0·1045	0·0001	68
DI 18229	1950	284·74 537·20	0·0948 0·0949	0·0948	—	0·0949	0·0001	81
DI 18230	1950	284·74 537·20	0·0942 0·0942	0·0942	—	0·0944	0·0002	17
DI 18231	1950	284·74 537·20	0·0956 0·0958	0·0957	—	0·0956	0·0001	13
DI 18232	1950	284·74 537·20	0·1047 0·1050	0·1048	—	*0·1046 (0·1047)	*0·0002 (0·0001)	—
DI 18233	1950	284·74 537·20	0·0958 0·0960	0·0959	—	0·0962	0·0003	—
DI 18234	1950	284·74 536·88	0·0950 0·0953	0·0951	—	0·0949	0·0002	—
DI 18235	1950	284·74 536·88	0·0950 0·0950	0·0950	—	0·0950	Nil	—
DI 18236	1950	284·74 537·20	0·0956 0·0956	0·0956	—	0·0958	0·0002	—
DI 18237	1950	284·74 537·20	0·0951 0·0950	0·0950	—	0·0950	Nil	—
DI 18238	1950	284·74 537·20	0·0960 0·0962	0·0961	—	0·0962	0·0001	—
DI 18239	1950	284·74 537·20	0·0953 0·0953	0·0953	—	0·0953	Nil	—

* Average of seven determinations. The figure in parentheses below is the average of the three, or two, test points corresponding to those of the original calibration.

SUMMARY

1. Observations over many years leave little doubt that deep-sea reversing thermometers, both of the protected and unprotected types, remain, with few exceptions, very reliable.

2. Failures to show an accurate temperature are few, only 447 being noted out of a total of 21,858 observations.

3. It is suggested that the reason for one type of erratic behaviour, hitherto not understood, may be due to some temporary physical change in the glass.

4. There is little difficulty in the field in reading temperatures to $\pm 0{\cdot}01^{\circ}$ C.

5. The use of a series of unprotected reversing thermometers on a cast of water-bottles to measure the depth at which the bottles closed will record these depths within a limit of approximately ± 1 m. for each 1000 m. of depth.

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Mention should also be made of the valuable work of the late Mr J. G. Durham of the N.P.L., who for many years calibrated and re-calibrated a large proportion of the deep-sea thermometers now under review.

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